

Historic Hydroclimatic Variability in Northern Mexico

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Abstract—The understanding of historic hydroclimatic variability is basic to plan for a proper management of limited water resources in northern Mexico. The objective of this study was to develop a network of tree-ring chronologies for climate reconstruction and to analyze the influence of circulatory patterns, such as ENSO. Climatic sensitive tree-ring chronologies were developed in mountain ranges of the Sierras Madre Oriental and Occidental. A grid of new Douglas-fir chronologies were developed and winter-spring precipitation reconstructions were produced for northwest Chihuahua, northwestern Durango, southern Nuevo Leon, and southeastern Coahuila. The seasonal winter-spring precipitation reconstructions extended 530 years (1472–2002) for Chihuahua, 228 year (1765–1993) for Durango, 602 years (1400–2002) for Nuevo Leon, and 342 years (1659–2001) for Coahuila. Some of the low frequency events were specific for each reconstruction, but low frequency events (decadal resolution) were present in most of the reconstructions; specific cases are the droughts of the 1810s, 1860s, 1870s, and 1950s, and the wet periods of the 1820s, 1830s, and 1890s. Trends in dry or wet periods were disrupted by above or below normal precipitation affected by the ENSO phenomena, especially in the winter–spring period when this circulatory pattern produced in times abundant rains in northern Mexico. However, the ENSO influence on Winter-Spring precipitation varied with time. Convective rains and precipitation from cyclones formed in the Gulf of Mexico may explain some of the hydrological variability detected in the southern Nuevo Leon and the southwestern Coahuila precipitation reconstructions. However, these preliminary results indicates that winter-spring hydroclimate variability in northern Mexico is influenced by a range of circulatory patterns, and a greater grid of tree-ring chronologies should be developed to explain in detail the involved climatic factors as well as to reconstruct Summer precipitation, that makes up more than 70 percent of the total annual precipitation.

Introduction

The study of historical variability of atmospheric circulatory patterns is basic to understand the current and future climatic changes and their effect on social and economical stability. The climate of northern Mexico is characterized by a seasonal precipitation regime and a strong monsoon component (Pyke 1972; Douglas and others 1993; Higgins and others 1999) with a pronounced maximum (> 70 percent) of annual rainfall in the warm season (May–October), and less than 30 percent on the rest of the year (Mosiño and García 1974).

Precipitation along northern Mexico varies on time scales ranging from seasonal to decades (Magaña and others 1999). Water supply is a major constraint on development and future land use practices in northern Mexico. However, the lack of available data about long-term trends and variability of water yields is a

significant limitation to planning the appropriate and future use of these resources. Water resource planning can greatly benefit from data on the range and variability of precipitation and streamflow that paleoclimatic studies can potentially provide. Therefore, the objective of this study was to examine the long-term hydroclimatic behavior over several hundred years by using tree-rings as a proxy data in developing precipitation reconstructions and analyzing the influence of circulatory patterns for northern Mexico. These data would allow the detection of low frequency periodicities that could be beneficial for the proper management of the limited water resources in this region.

In this study long-term Winter-Spring precipitations reconstructions for the states of Chihuahua, Durango, Coahuila, and Nuevo Leon were developed from the early wood chronologies of Douglas-fir tree rings collected at several locations in the Sierras Madre Occidental and

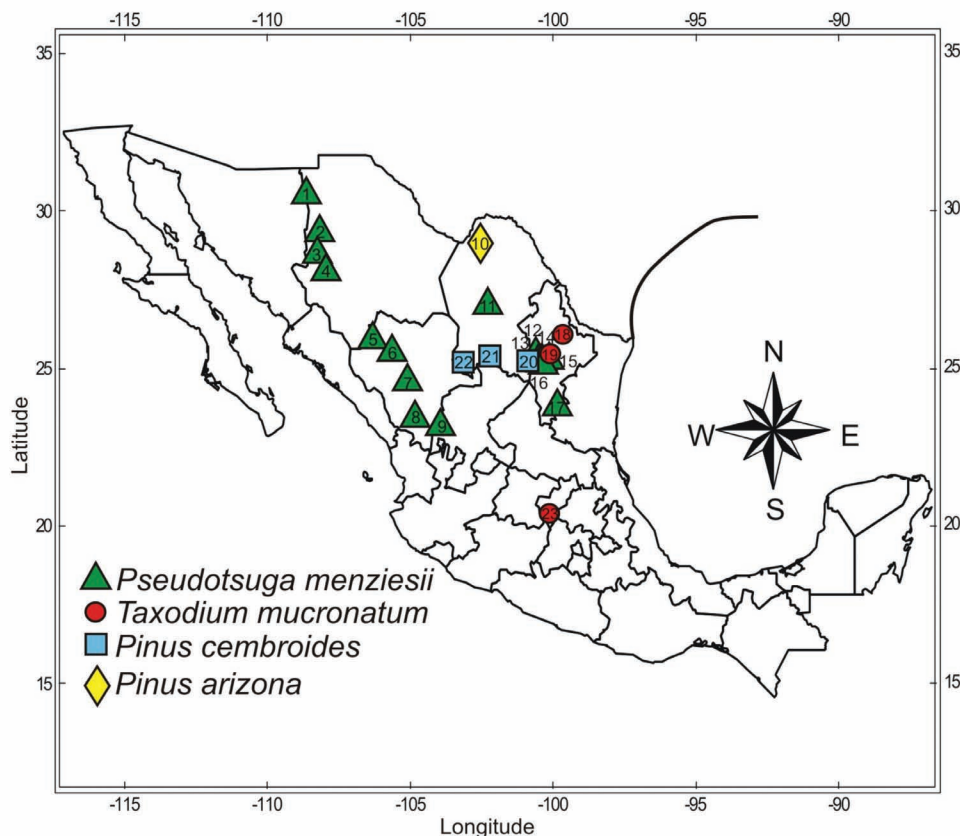


Figure 1. Geographical distribution of new tree-ring chronologies recently developed in northern Mexico.

Site name	Chronology	Elev. (m)	Site name	Chronology	Elev. (m)
1. Mesa de las Guacamayas	1636-2002	2665	13. Pílares	1855-2000	3150
2. Madera	1774-2001	2820	14. La Viga	1659-2001	3400
3. Bisaloachi	1537-2002	2744	15. Coahuilón	1700-2001	3200
4. Cebadillas de Ocampo	1588-2002	2781	16. El Morro	1872-2000	3500
5. El Cocono	1450-2002	1950	17. Mesa de los Gatos	1400-2002	3200
6. Ciénega de la Vaca	1763-2002	2800	18. Cerralvo	1741-2003	1280
7. Cerro Bandera	1675-2001	3170	19. Río San Juan	1887-2003	1240
8. Las Bayas	1681-2001	2980	20. Sierra Zapalinamé	In process	
9. Jiménez de Teúl	1758-2001	2758	21. Sierra de Parras	In process	
10. Maderas del Carmen	1761-2002	1700	22. Sierra de Jimulco	In process	
11. Sierra Cuatro Ciénegas	1719-2003	2180	23. Barranca de Amealco	In process	
12. El Tarillal	1775-2000	3200			

Oriental. These reconstructions are then analyzed and linked to large scale climatic forcing. The presence of dry and wet episodes on the reconstructions is validated with historical documents (when available) as a way to showing human responses to climatic extremes. It would be important to capitalize this information for a proper management of water resources on this extent dry region.

Methodology

Tree Ring Chronologies

In an attempt to extend existing short hydrological records tree-ring chronologies were developed from increment cores and cross sections taken mostly from Douglas-fir trees (*Pseudotsuga menziesii*) growing in mixed conifer stands along the Sierras Madre Occidental and Oriental in the states of Chihuahua, Durango,

Coahuila, and Nuevo Leon. The sampled trees were selected from relatively undisturbed stands in sites classified as with low productivity to maximize the climatic signal. The cores were mounted, sanded and crossdated using standard procedures (Stokes and Smiley 1968) and tree-ring series were measured with a VELMEX “TA” stage micrometer at 0.001 mm resolution. Crossdating and measurement quality were verified with COFECHA, (Holmes 1983, Grissino-Mayer 2001). New tree-ring chronologies of earlywood (EW), latewood (LW) and total ring width (RW) were developed for new Douglas-fir sites and combined with recent chronologies from the region (fig. 1).

Ring-width measurements were standardized with ARSTAN (Cook 1987). All series were initially detrended either with a negative exponential curve or a straight line with a negative slope and secondly with a smoothing spline of 50 percent wavelength (Cook and Peters 1981). Principal Component Analysis (PCA) was performed on

the grid of available chronologies to identify orthogonal modes of tree growth (Fritts 1976).

The relationships between climate and tree-growth were investigated by correlation and response-function analysis. A decadal smoothing spline was fitted to the reconstructed series to emphasize the decadal variance (Cook and Peters 1981). When possible, reconstructed drought periods were validated with historical documentation.

Climate Records

Meteorological information was obtained from the climatic data base ERIC II (IMTA 1977); the National Climatic Data Center's Global Historical Climatology Network (GHCN), and from individual meteorological stations of the Comision Nacional del Agua (2002). Missing data were estimated by Paulhus and Kohler's method (1952), and double-mass analysis (Kohler 1949) was used to test homogeneity between stations.

Precipitation Reconstructions

Historical cool season precipitation reconstructions were developed for the states of Chihuahua, Durango, Coahuila, and Nuevo Leon. Climatic information from the 4532 grid (GHCN) was related to the EW Douglas-fir chronologies from Chihuahua. Likewise, the Guanaceví meteorological station was associated to the first principal component values of a network of early wood chronologies for Durango (EW PC1). Douglas-fir chronologies from southern Nuevo Leon were associated to the mean climatic conditions from several meteorological stations located in the states of Nuevo Leon and Tamaulipas, and the meteorological station Saltillo was associated to the network of early wood chronologies from the Sierra de Arteaga, Coahuila.

Results and Discussion

Precipitation Reconstruction for Northeastern Chihuahua

It was found a significant correlation between the EW chronology from Bisaloachi, Chihuahua and the seasonal precipitation (October–May) for the 4532 climatic grid (fig. 2). The regression estimates were tested against independent climatic data with a variety of statistical measures (Fritts 1991). The climatic data was most reliable for the period 1950 to 1990. Therefore, the tree-ring data was regressed from the 1950 to 1990, 1950 to 1969, and 1970 to 1990 periods against the corresponding climatic data. Because statistical tests validated the two subperiods and the regression coefficients did not



Figure 2. Location of the climatic grid 4532, developed by the National Climatic Data Center's Global Historical Climatology Network (GHCN).

differ significantly (results not shown), the 1950–1990 regression relationship was used to reconstruct winter-spring precipitation. In general terms, the earlywood width explained more than 50 percent of the precipitation variance.

The model used for reconstruction was:

$$\hat{Y}_t = -111.7637 + 290.693X_t$$

Where \hat{Y}_t is the estimated total October–May precipitation (mm) and X_t is the Bisaloachi EW chronology indices.

The Winter–Spring (October–May) precipitation reconstruction, period 1472 to 2002 shows the presence of frequent droughts affecting northwestern Chihuahua along 530 years of the reconstruction (fig. 3).

The worst 20th century drought occurred in the 1950s and 1960s. Similar drought episodes were detected in climatic reconstructions for Durango by Cleaveland and others (2003), Gonzalez-Elizondo (2003), and partially coinciding with a severe drought in Texas (Griffith and Ainsworth, 1981). A more intense drought was observed in the XVIII century, period 1767 to 1778, also detected in a precipitation reconstruction for northern Sonora (Villanueva and McPherson 1999). The drought of the 1550 to 1570 has been reported as one of the most severe for northern Mexico in the last 600 years (Cleaveland and others 2003), although this drought was of lower length and intense on this reconstruction. One shorter severe drought was observed between 1488 and 1496, apparently affecting other areas of the Sierra Madre Occidental (Cleaveland and others 2003). This seasonal

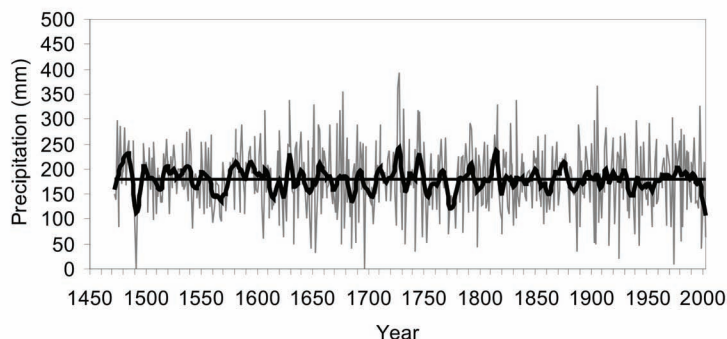


Figure 3. Seasonal Winter-Spring precipitation reconstruction (October–May), period 1472 to 2002, for western Chihuahua and eastern Sonora (climatic grid 4532). The mean precipitation for the reconstructed period was 143.2 mm (solid line) with a standard deviation of 52.4 mm. A smoothing spline has been fitted to the reconstruction to emphasize long-term droughts for the periods 1488-1496, 1552-1573, 1611-1626, 1767-1778, 1882-1887, 1945-1960, 1993-2002. Wet episodes were observed in the periods 1477-1486, 1590-1598, 1649-1661, 1736-1750, 1820-1824, 1873-1878, 1940-1944, and 1972-1979.

precipitation reconstruction provides a good estimation of the hydroclimatic variability of northwestern Chihuahua and eastern Sonora where the climatic quadrant 4532 is located, and verifies a shorter seasonal precipitation reconstruction (1647 to 1992) previously developed for the state of Chihuahua (Diaz-Castro and others 2002).

Precipitation Reconstruction for the Upper Nazas Watershed, Durango

Tree-ring chronologies were developed in the Nazas watershed and compared to climatological stations scattered on this basin (fig. 4).

The regression analysis between the first principal component of 9 Douglas-fir chronologies and the Winter–Spring precipitation (November–May) for Guanacevi climatic station calibrated 73 percent and 57 percent in the two subperiods (1941 to 1966, 1967 to 1993, respectively) and 63.7 percent over the full period (1941 to 1993). The reconstruction models pass all the statistical tests of accuracy.

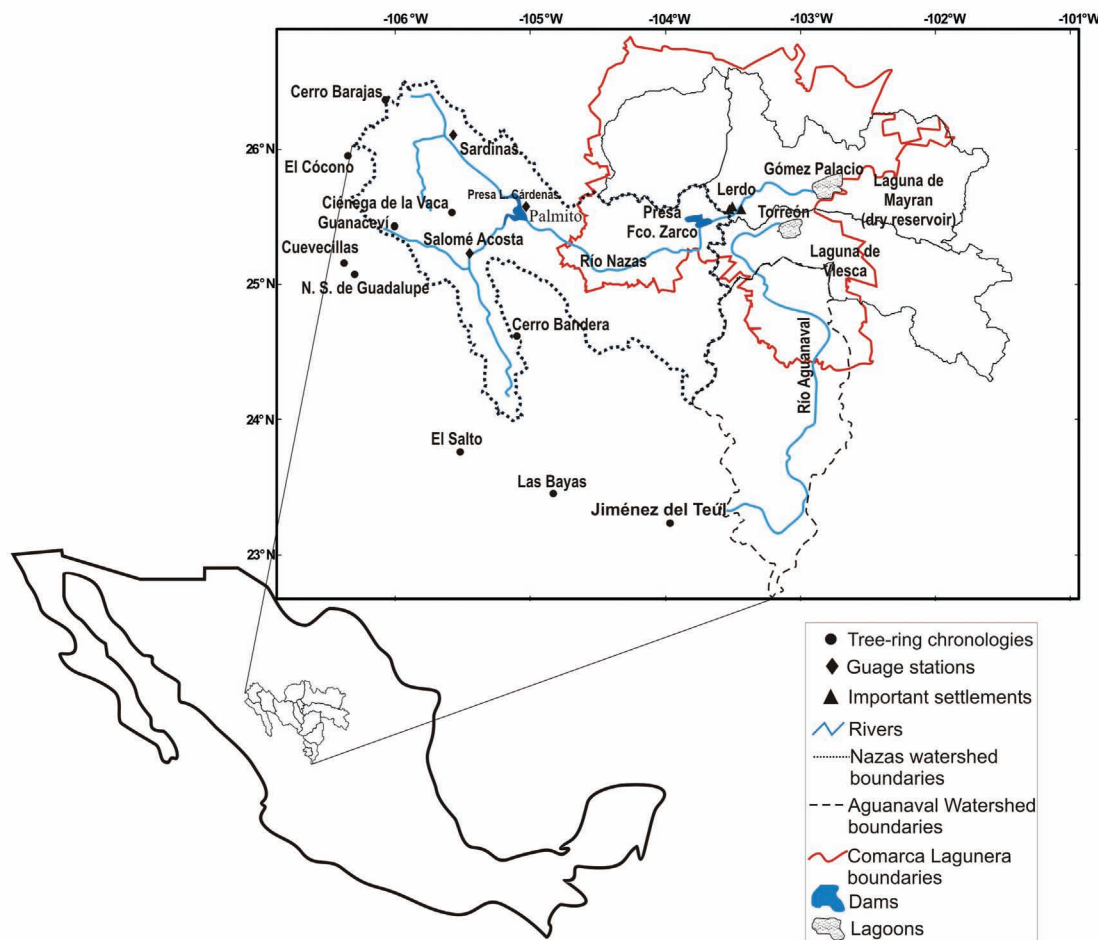


Figure 4. Distribution of tree-ring chronologies, climatic stations, and important settlements in the Nazas watershed, Durango, Mexico.

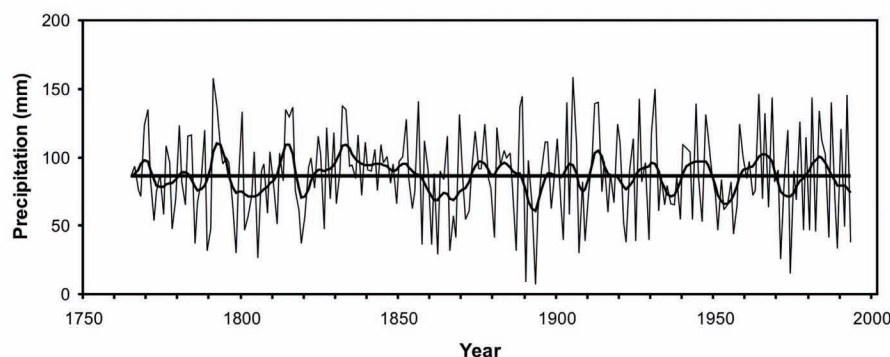


Figure 5. Reconstructed Winter–Spring precipitation (November–May) from 1765 to 1993 for the upper Nazas watershed, Durango, Mexico. A decadal smoothing spline fitted to the annual data emphasizes low frequency variance in the reconstruction.

The precipitation reconstruction covers the period from 1765 to 1993, the common period of all chronologies. The reconstruction is conservative and underestimates precipitation in isolated years of high precipitation, but provides the high and some medium frequency precipitation variability and is a good indication of past dry periods at decadal scales (fig. 5).

Similar to the Chihuahua reconstruction, this reconstruction shows a drought in the 20th century occurred between 1950 and 1957 with a mean winter-spring precipitation of 65.1 mm, 25 percent below the average of the reconstruction (86.5 mm). The 1950s drought has been identified by Cleaveland and others (2003) for Durango and in several regions across Mexico (Therrell and others 2002) and the southwestern United States (Cook and others 1999). Florescano (1980) identified the 1950, 1951, and 1956 years as some of the most extreme droughts for northern Mexico. Based on the precipitation reconstruction there are several drought episodes of similar or greater intensity to those in the 20th century. In the drought of the 1890's (1880 to 1896) and 1900's (1907 to 1910) precipitation was, respectively, 15 and 35 percent lower than the mean. Although the 1890's drought was not as severe as some of the 20th century droughts, it lasted almost two decades and was followed by a short intense drought. Documentary records suggest it led to a drastic reduction in grain production in northern Mexico (Garcia-Acosta 1993), reduced the water volume for irrigation on the Comarca Lagunera (Teran-Lira 2000) and may have contributed to the unrest that triggered "The Mexican Revolution" that started in 1910 (Escobar-Ohmstede 1997). The reconstructed record suggests that 1857 to 1872 was one of the longest droughts with an average of 71.2 mm (18 percent below the reconstructed mean value). Notwithstanding the length of this drought, few historical documents talk about this difficult period when food shortages and famine were common in the region, although Garcia-Acosta (1993) inferred a severe drought in Durango in 1867 based on food prices. An additional drought episode was reconstructed from 1797 to 1811. The linkage between this and previous droughts,

shortage of food, famine, and presence of pests produced social discontent that fuelled the movement for independence known as "The Independence War of Mexico" (Garcia-Acosta 1993).

Several of the wetter intervals in this reconstruction have also been identified in adjacent regions and extended across much of the western USA (Fye and others 2003).

Precipitation Reconstruction for Saltillo, Coahuila

A seasonal Winter–Spring (January–June) precipitation reconstruction was developed for Saltillo, Coahuila (fig. 6). In producing this reconstruction, five Douglas-fir earlywood chronologies developed from mixed-conifer stands along the Sierra de Arteaga, Coahuila were involved (e.g. La Vega, El Coahuilon, Los Pilaes, El Tarillal, and El Morro). The average chronology from La Vega, El Coahuilon, and Los Pilaes resulted to be more significantly correlated with the total seasonal precipitation January–June for the meteorological station Saltillo. Therefore, a bivariate regression model explaining more than 60 percent of the precipitation variance was built to reconstruct a seasonal precipitation for this region (fig. 7). The reconstruction of 342 years (1659–2001) extends 123 years back in time a previous precipitation reconstruction based exclusively in one site chronology produced by Pohl and others (2003) for this region.

Similar to the previous reconstructions, droughts were common along the 20th century, especially for the 1950s and 1960s. In the 19th century some of the severe droughts detected on this reconstruction took place in the 1890s, 1860s, and 1810s. Additional droughts were detected for the period 1720 to 1740, 1690s, and 1670s. Many of this droughts produced agricultural crisis and limited food availability, especially the ones observed at the end of the XVIII and XIX centuries (Cuellar-Valdéz 1979; García-Hernández 1997). The economical and social effects of droughts are increasing in intensity, extension, and duration for this region due in part to

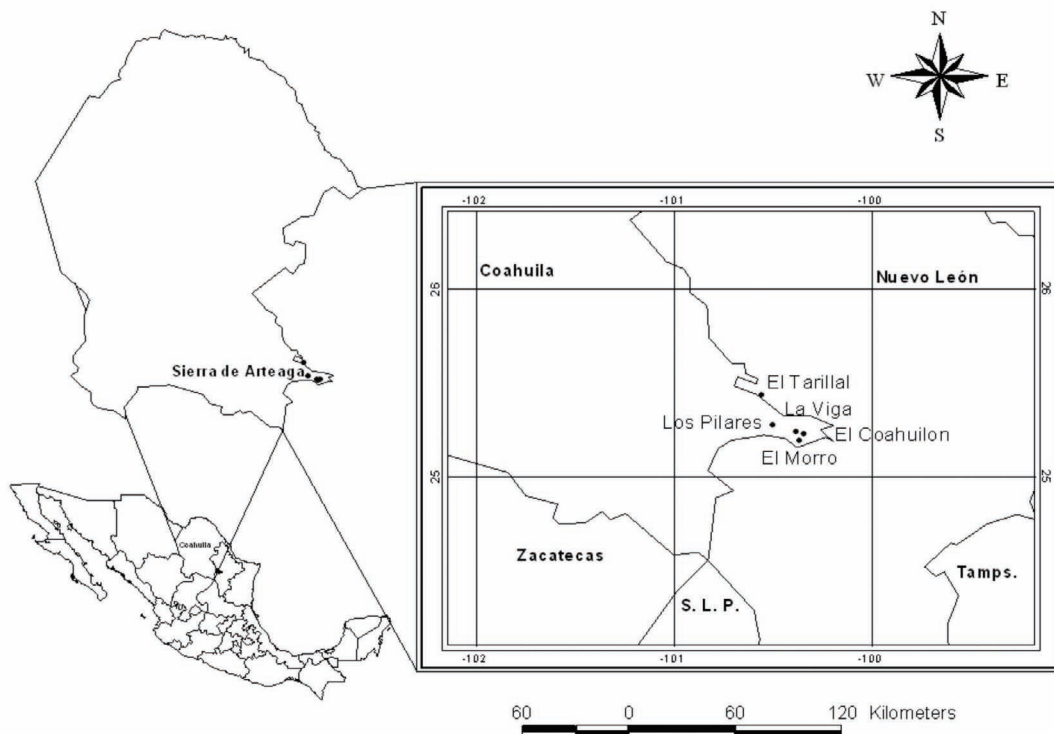


Figure 6. Geographical distribution of the earlywood Douglas-fir chronologies developed from collections located in the Sierra de Arteaga, Coahuila. Some of these tree-ring chronologies were used to develop a cool season precipitation reconstruction for the region.

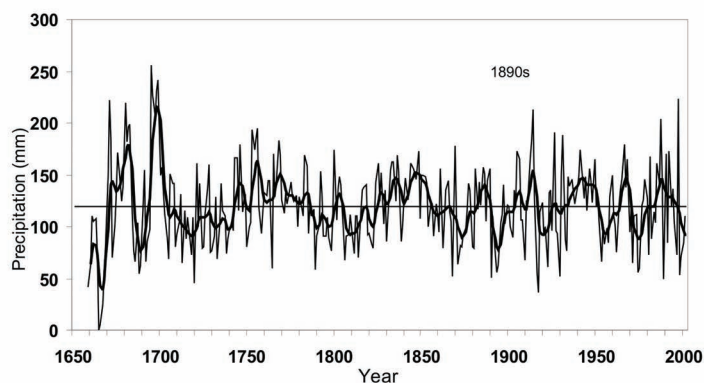


Figure 7. Seasonal Winter-Spring precipitation reconstruction (January – June), period 1659 – 200 for Saltillo, Coahuila. A smoothing spline has been fitted to the reconstruction to emphasize long-term droughts like the ones in the 1950s, 1870s, 1790s, 1690s, and 1670s.

the higher water demand for industrial, agricultural, and different human uses. The establishment of human settlements in places prone to droughts is exacerbating the effect of natural climate variability not only on this region but all over Mexico.

Precipitation Reconstruction for Central and Southern Nuevo Leon

One of the longest precipitation reconstructions for northeastern Mexico is the one derived from an early-wood Douglas-fir chronology located in the site Peña

Nevada, Nuevo Leon. This chronology of 602 years length was significantly correlated with the seasonal Winter-Spring (December–April) precipitation for a grid of climatic stations located in central, southern and western Tamaulipas covering the period 1964 to 1997 (fig. 8). The calibration and verification procedures were statistically significant. A bivariate linear equation considering the total length of instrumental data indicated that the tree-ring chronology is explaining close to 50 percent of the seasonal variability of precipitation for this area.

The seasonal precipitation reconstruction (December–April) shows the presence of recurrent droughts affecting this region along the period of 1402 to 2002 (602 years) (fig. 9). On the 20th century the most significant drought episodes took place in the periods 1968 to 1975 and 1952 to 1956. Additional low water availability was also detected on the periods 1857 to 1868, 1785 to 1790, 1738 to 1743, 1559 to 1590, 1526 to 1536, and a severe drought between 1459 and 1467. Some of the droughts observed in this reconstruction have been documented by Florescano (1980), especially the ones occurred in the 1950s and 1860s, similarly present in other precipitation reconstructions for northern Mexico. The lack of historical documents for this region has prevented a proper verification of the reconstructed data before the 1850s. However, it is amazing how droughts affecting other regions of Mexico were also observed in this reconstruction. A specific case is the severe drought of the 1450s and



Figure 8. Geographical distribution of climatic stations (1. Allende, 2. Iturbide, 3. Casillas, 4. Ciénega del Toro, 5. Cerralvo, and 6. UValles) involved in a precipitation reconstruction for Nuevo Leon and Tamaulipas.

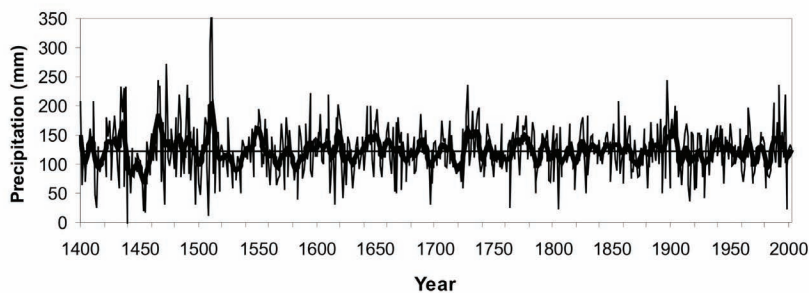


Figure 9. Seasonal Winter–Spring (December–April) precipitation reconstruction, period 1400–2002 for southern Nuevo Leon and eastern Tamaulipas. The smoothing spline emphasizes low frequency events. Drought episodes were observed in the periods 1439 to 1455, 1526 to 1536, 1559 to 1590, 1738 to 1743, 1857 to 1868, 1915 to 1922, and 1968 to 1975.

1460s in the Valley of Mexico that produced shortage of food and drinking water for the Aztec civilization.

A more detailed historical analysis would be important to support hydroclimatic studies in this region that has a great potential in socio-economical terms for Mexico.

ENSO Teleconnection to the Northern Mexico Precipitation Reconstructions

The cool season precipitation in northern Mexico and southwestern United States is strongly linked with the Southern Oscillation Indices (Ropelewski and Harper 1989; Stahle and others 1998, Magaña and others 1999). This relationship is clearly recorded in the tree rings of Douglas-fir growing in the Sierras Madre Oriental and Occidental.

The ENSO extra-tropical teleconnection in northern Mexico is quite strong, but the strength and spatial extent varies over time (Cleaveland and others 2003). The lack of stability is illustrated with the variability of correlation with the Tropical Rainfall Index (TRI) an estimate of the ENSO variability using rainfall anomalies in the central Pacific (Wright 1979). This statement is validated when comparing the TRI and the precipitation reconstruction for Chihuahua for the 1896 to 1995 period. Correlations in successive 20-year periods varied in a range of 0.2 to 0.69. Similar correlations values were found for the Durango reconstruction (Cleaveland and others 2003).

The relationship between the TRI and the Saltillo reconstruction was highly variable and the correlations ranged from 0.24 to 0.65. The highest correlation value of 0.65 was found before 1915 and the lowest ($r = 0.24$) after this subperiod (fig. 10).

A changing relationship was found between the TRI and the Nuevo Leon precipitation reconstruction. The correlation values were higher before 1900 and decreased along the 20th century.

The response of the northern Mexico precipitation to ENSO forcing appears to be strongest during warm ENSO events (El Niño), based on the correlation analysis with the TRI (Cleaveland and others 2003). On the other hand, the extended and similar drought episodes recorded in most of the precipitation reconstructions apparently were influenced by cold ENSO events (La Niña). However, other atmospheric circulatory patterns may have influenced the observed precipitation variability, especially for those reconstructions located in northeastern Mexico (Saltillo, Nuevo Leon), where cyclones, tropical storms, and other atmospheric patterns may influence much of the winter and summer precipitation which source of water is mostly the Gulf of Mexico (Magaña and others 1999).

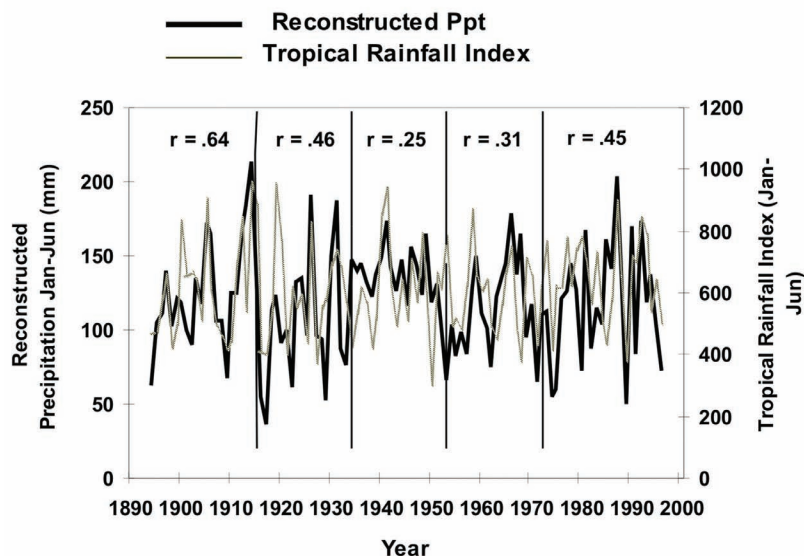


Figure 10. Correlation (r) of the Winter–Spring (January–June) Tropical Rainfall Index with reconstructed Saltillo January–June precipitation in 20-year periods, a demonstration of the long-term instability of the Pacific equatorial teleconnection with northeastern Mexico climate.

Historical Climatic Low Frequency Trends Detected on the Precipitation Reconstructions

The presence of low frequency events were significantly correlated ($p < 0.05$) for the common period of the reconstructions (1782 to 1992), especially on those reconstructions developed for a specific mountain range. Precipitations reconstructions along the Sierra Madre Occidental indicated high and significant correlations ($r = 0.08$, $p < 0.01$). Likewise, lower correlation coefficients ($p > 0.05$) were found when precipitation reconstructions

were compared between mountain ranges (table 1). This finding has significant implications to analyze the influence of climatic systems in a particular mountain range and indicates that the hydroclimate variability in northern Mexico is probably being influenced by different circulatory patterns or similar atmospheric phenomena but modulated by changing physiographic conditions that characterizes the Sierras Madre Occidental and Oriental, located along the western and eastern sides of northern Mexico, respectively.

Notwithstanding the influence of well defined atmospheric circulatory patterns affecting a particular mountain range is surprising the presence of generalized dry or wet episodes that affected extensive areas of Mexico. The droughts of the 1810s, 1860s, 1870s, and 1950s were detected in all of the reconstructions (fig. 11). These droughts produced shortages of food, fires, and epidemic outbreaks (Fulé and Covington 1999; Acuña-Soto and others 2002). The presence of these general events indicates that atmospheric circulatory patterns of greater extent such as ENSO and the Southwestern Monsoon System may be causing this climatic behavior. Therefore, they should be considered and analyzed in a greater detail for a better understanding of climate in the Republic of Mexico.

Conclusions

The cool season precipitation reconstructions developed for several places of northern Mexico indicated droughts of greater intensity and extent than those witnessed along the 20th century. These reconstructions

Table 1. Correlation coefficient values for several winter-spring precipitation reconstructions for a common period (1782 to 1992). All correlation values were significant ($p < 0.001$) but the highest values were obtained when comparing reconstructions developed for a particular mountain range, which is an indication of the influence of different atmospheric circulatory patterns in tree growth.

Winter–Spring precipitation reconstructions in northern Mexico	Ppt Oct–May Bisaloachi, Chihuahua ¹	Ppt Nov – April, Chihuahua (Diaz and others 2002) ¹	Ppt Nov - March Durango, (Cleaveland and others 2003) ¹	Ppt Jan – June Saltillo, (Pohl and others 2003) ²	Ppt Dec – April Peña Nevada, N.L. ²
Ppt Oct–May, Bisaloachi, Chihuahua ¹	1.0				
Ppt Nov–April, Chihuahua (Diaz and others 2002) ¹	0.79	1.0			
Ppt Nov–March, Durango, (Cleaveland and others 2003) ¹	0.65	0.78	1.0		
Ppt Jan–June, Saltillo, (Pohl and others 2003) ²	0.38	0.43	0.56	1.0	
Ppt Dec–April, Peña Nevada, N.L. ²	0.33	0.37	0.51	0.49	1.0

¹ Precipitation reconstructions for the Sierra Madre Occidental.

² Precipitation reconstructions for the Sierra Madre Oriental.

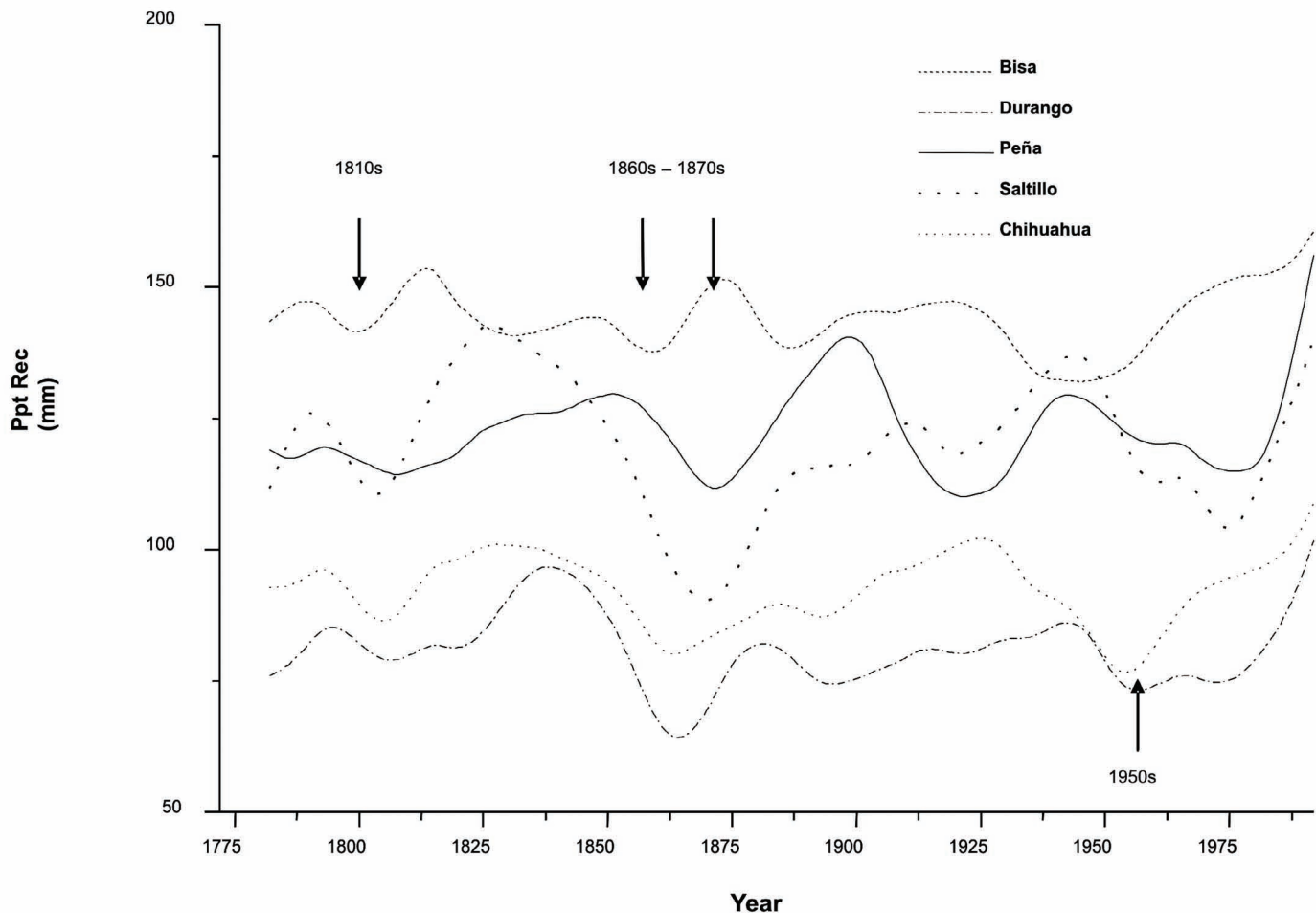


Figure 11. Low frequency events common to all precipitation reconstructions for northern Mexico. The arrows show dry periods present in most of the reconstructions such as the 1810s, 1860s, 1870s, and 1950s. Generalized low frequency events are attributed to the influence of atmospheric circulatory patterns (e.g. ENSO, SMS).

are well correlated with the ENSO indices and offer an excellent opportunity to further explore the history and variability of the Southern Oscillation. All reconstructions showed strong and variable in times seasonal correlations to the Tropical Rainfall Index indicating the necessity to explore in detail the ENSO circulatory pattern that explains much of the great scale cool season hydroclimatic variability in central and northern Mexico.

The expanding network of tree-ring chronologies now available for several regions of Mexico and composed by different species will play in a short future an important role in reconstructing Mexico's late Holocene paleoclimate variability.

Additional sensitive baldcypress (*Taxodium mucronatum*) chronologies over a thousand years have been developed in the last few months for the central region and some shorter for northern Mexico. These

chronologies have the potential to provide seasonal rainfall reconstructions and may help to explain the warm season precipitation variability that accounts for more than 70 percent of the annual total precipitation for central and northern Mexico, and that has been linked to the Southwestern Monsoon System. Summer rainfall is of main importance for agriculture, grassland productivity, ground water recharge, etc, and understanding its historic variability may help to plan for a proper management of this limiting resource in Mexico.

The lack of suitable proxy climatic records in the past has limited proper hydroclimatic analysis for water management and climate forecasting purposes. The new network of tree-ring chronologies in expanding process linked to historical socioeconomical data will help to explore relationships that may contribute to plan in advance the better management of limited water resources in central and northern Mexico.

Acknowledgments

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